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Health hazards from fission products and fallout

II. Gamma radiation from nuclear weapons fallout [1]

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With 7 figures in the text

Introduction

In an estimate of the health hazards from nuclear weapons fallout some knowledge of the gamma energy distribution is essential. This is evident when one considers the large areas that may become covered with fallout in a nuclear war, the large number of people that may be affected and the resulting desirability of protectionary procedures, e.g. shelters and radiac instruments, the efficiency of which are largely dependent on the actual gamma energy distribution from fallout. In ascertaining the importance of an accurate knowledge of this gamma distribution one could furthermore point to the fact that measurements of the gamma spectrum have become a useful method for the identification of fission product mixtures and the determination of their composition and age.

There exist a number of ways to estimate the gamma radiation from fallout and other fission product mixtures. The first method was proposed in 1945 by Way and Wigner [2]. It is largely theoretical, considering the fission products as a statistical assembly. On the basis of the hypothesis of equal charge displacement, Weiszäcker's semiempirical mass formula and an approximate relationship between decay constant and total decay energy, it is possible to derive directly the total radiation from all fission products together. This method is simple and the results are in fairly good agreement with experimental data. Yet there are two drawbacks important in this connection. In the first place (as pointed out by the authors) the statistical model does not apply well at long times after fission when the number of radiating nuclides is small. Secondly a calculation of this kind gives no information about the radiation spectra at different times after fission. For these reasons the above method has to be termed insufficient as a basis for an evaluation of the health hazards discussed here.

A second way to arrive at the gamma energy distribution from a fission product mixture is to consider it as the sum of radiations from the individual fission products. This method can somewhat arbitrarily be considered to consist of two parts, the first part (1 in table 1) being a calculation of fission product decay rates starting from chain and individual yields, decay constants and branching ratios and the second

Table 1. Data on simultaneous fissions.

Reference	Published	Fission	S or C	1 or 2	Time	Yields	Decay data	Comments
Hunter, Ballou [4]	1949	U^{235}, n_{th}	S	1	1 s–100 y	1948	1948	Only total decay. No γ spectra.
Howlett, Josephs, Rennie, Story [5]	1950	U^{235}, n_{th}	S, C	1, 2	1 d–1000 d	1950	1950	Only total β- and γ-ener gies are given. No γ-spec tra. (U^{238}, n_f) is briefly con sidered.
Faller, Chapman, West [6]	1952	U^{235}, n_{th}		1				Reference not available.
Heiman [7]	1952	U^{235}, n_{th}	S	2		1948		Reference classified. Base on (4).
Thornton, Houghton [8]	1953	U^{235}, n_{th}	S, C	1	0–100 y	1946	1946	Only the total decay rat is given.
Moteff [9]	1953	U^{235}, n_{th}	C	1, 2	3 h–10 d	1951	1952	Seven gamma energ groups. 24 nuclides consid ered.
Clark [10]	1954	U^{235}, n_{th}	C	1, 2	3 h–3 y	1954	1954	Seven gamma energ groups. Extension of (9).
Heiman [11]	1954	U^{235}, n_{th}	S	2		1948		Reference classified. Base on (4).
Björnerstedt, Löw, Ulvönäs [12]	1955	U^{235}, n_{th} Pu^{239}, n_{th}	S	1, 2	1 h–3 y	1951	1954	30 gamma energy groups 45 nuclides considered.
Frederick [13]	1955	U^{235}, n_{th}	C	1	14 d–420 d	1954	1954	No γ-spectra.
Bolles, Ballou [14]	1956	U^{235}, n_{th}	S	1	0 s–550 y	1951	1953	Extension of (4).
Miller [15]	1957	U^{235}, n_{th}	S	2	45 m–300 y	1951	1953	Based on (14). No γ-spec tra.
Dillon, Burris [3]	1957	U^{235}, n_f Pu^{239}, n_f	C	1, 2	200 d–10 y	1955	1955	Only total γ-decay is giv en.
Löw, Björnerstedt (I)	1957	U^{235}, n_{th}	S	1	1 h–100 y	1957	1956	Extension of (12). No γ spectra
Blomeke, Todd [16]	1957–1958	U^{235}, n_{th}	C	1, 2	25 d–30 y	1955	1955	4 gamma energy groups 112 nuclides considered.
Prawitz, Rydberg [17]	1958	U^{235}, n_{th}	C	1	20 d–15 y	1957	1957	No γ-spectra.
Perkins, King [18]	1958	U^{235}, n_{th}	S, C	1, 2	100 s–3 y	1957	1957	7 gamma energy groups 110 nuclides considered Extension of (10).
Scoles [19]	1958	U^{235}, n_{th}	C	1, 2	1 d–400 d	1957	1957	6 gamma energy groups.
Miller, Loeb [20]	1958	U^{235}, n_{th}	S	2				Reference not available.
Prawitz, Löw, Björnerstedt [III]	1958	U^{235}, n_{th}	C	2	20 d–15 y	1958	1958	15 gamma energy groups 73 nuclides considered Based on (17).
Knabe, Putnam [21]	1958	U^{235}, n_{th}	S, C	2	1 s–3 y	1957	1957	12 gamma energy groups Extension of (18).
Leipunskii [22]	1959	U^{235}, n_{th} Pu^{239}, n_{th}	S	1, 2	1 h–100 y	1956	1956	3 gamma energy groups.
Nelms, Cooper [23]	1959	U^{235}, n_{th}	S	2	30 m–120 y	1951	1957	22 gamma energy groups 128 nuclides considered Based on (14).
Present work	1959	U^{235}, n_{th} U^{235}, n_f Pu^{239}, n_f U^{238}, n_f U^{238}, n_{14} U^{235}, n_{14}	S	2	1 h–100 y	1959	1959	50 gamma energy groups 118 nuclides considered Based on I. Extension o III.

part (2 in table 1) comprising a combination of the decay rates with known or assumed decay schemes to give the composite gamma (or beta) spectrum.

It is evident that a calculation of this second kind gives results, the accuracy of which are dependent upon the fission yield values and decay data used. All calculations published, with one exception [3], refer to thermal neutron fission. It is often assumed that a fission product mixture of this kind can be taken as representative of nuclear weapons fallout when health hazard estimates are concerned. This assumption will be discussed later with special reference to the gamma energy distribution.

The existing calculations are reviewed in table 1. They may be divided into two groups, considering simultaneous or continuous fissions (S or C in the table). Only calculations of simultaneous fissions are of interest here, yet it should be noted that for cooling times much longer than the irradiation time data on continuous fissions (the reactor case) may be used. If, as in table 1, a cooling time twenty times longer than the irradiation is used, the results apply with an error of less than one percent to simultaneous fissions (III).

References [9, 10, 12, 16, 18, 19] III, [21] and [23] are of primary interest as they present information about the gamma spectra at different times after fission. Some of these references supersede earlier work [9, 10] and [12]. Considering times after simultaneous fissions from one hour and onwards (as in this paper), the work of Knabe and Putnam [21] replaces that of Perkins and King [18]. Finally for simultaneous fissions the results from 20 days to 15 years of ref. III are replaced by this paper. The work which may be used for comparisons with this work is thus [16, 19, 21] and [23].

A third way of getting information on fission product mixtures is through direct measurements. The gamma decay at one hour or later after simultaneous fissions has been studied in a number of experiments, the more important of which are listed as ref. [24–30]. Measurements on nuclear weapons fallout are however very few, as these results are often classified. In addition fractionation phenomena make the analyses difficult. For these reasons and because of the rather bad energy resolution of the methods employed, it is at present impossible to use only experimental data when evaluating health hazards from fallout gamma radiation.

Method of calculation

The calculation may in principle be considered to consist of three parts:

1. derivation of decay rates for 10^4 simultaneous U^{253} fissions.
2. combination of the decay rates with data on number of γ-quanta of different energies per disintegration.
3. computation of γ-spectra for other fission modes through correction of (U^{253}, n_{th}) yield data with respect to other sets of fission yields.

The first part of the calculation is based on Löw, Björnerstedt [I]. A number of changes have however been made on account of more recent data on fission yields, half lives and branching ratios [31–41]. 32 isotopes were affected but the changes were mostly rather small. Major alterations were made for Tc^{99m}, chains 126, 127, 128 and Sb^{130}. The input data are now current as of July 1959. The same applies to the input data used in the second part of the calculation which was based on Prawitz, Löw, Björnerstedt (III) and some additional data [18; 35–47]. The γ-lines of some

Table 2. Nuclear data used in the calculation.

Nuclide	Half life	*a, b, c, d**	U^{235}, n_{th}	U^{235}, n_f	Pu^{239}, n_f	U^{238}, n_f	U^{238}, n_{14}	U^{235}, n_{14}
Ge^{78}	86 min		0.02	0.02	0.00	0.009	0.066	0.15
As^{78}	91 min	$a=1$	—	—	—	—	—	—
Se^{83}	25 min		0.21	0.14	0.036	0.15	0.26	0.39
Br^{83}	2.3 h	$a=1$	0.34	0.23	0.059	0.24	0.41	0.64
Kr^{83m}	1.9 h	$a=1$; $b=1$	—	—	—	—	—	—
Br^{84}	33 min		1.00	0.62	0.19	0.82	0.89	1.45
Kr^{85m}	4.36 h		1.30	1.13	0.32	0.64	1.14	1.87
Kr^{85}	10.27 y	$a=0.225$	—	—	—	—	—	—
Kr^{87}	78 min		2.49	2.87	0.79	1.79	1.76	3.18
Kr^{88}	2.77 h		3.53	3.47	1.23	2.32	2.09	3.56
Rb^{88}	17.8 min	$a=1$	—	—	—	—	—	—
Rb^{89}	15.4 min		4.78	4.15	1.44	2.81	2.49	4.11
Sr^{89}	50.5 d	$a=1$	—	—	—	—	—	—
Sr^{90}	27.7 y		5.74	4.38	2.23	3.10	2.91	4.21
Y^{90}	64.5 h	$a=1$	—	—	—	—	—	—
Rb^{91m}	14 min		5.70	5.09	2.60	3.56	3.21	4.38
Sr^{91}	9.7 h	$a=1$	0.20	0.18	0.09	0.12	0.11	0.15
Y^{91m}	51 min	$a=0.60$	Sr^{91}—	—	—	—	—	—
Y^{91}	58 d	$b=1.00$ $c=0.40$	Sr^{91}—	—	—	—	—	—
Sr^{92}	2.7 h		6.10	5.26	3.21	4.16	3.73	4.68
Y^{92}	3.6 h	$a=1$	—	—	—	—	—	—
Y^{93}	11.0 h		6.50	5.38	3.64	4.64	4.05	4.91
Y^{94}	16.5 min		6.50	5.65	4.08	5.13	4.41	4.96
Y^{95}	10.5 min		6.40	6.72	5.12	5.52	4.69	5.15
Zr^{95}	63 d	$a=1$	—	—	—	—	—	—
Nb^{95}	35 d	$b=1$	—	—	—	—	—	—
Nb^{95m}	90 h	$b=0.01$	—	—	—	—	—	—
Zr^{97}	17.0 h		6.20	6.51	5.05	5.42	5.52	4.54
Nb^{97m}	60 sec	$a=0.91$	—	—	—	—	—	—
Nb^{97}	72.1 min	$a=1.00$	—	—	—	—	—	0.59
Mo^{99}	67 h		6.10	6.10	5.73	6.10	5.81	4.84
Tc^{99m}	6.04 h	$a=0.9$	—	—	—	—	—	—
Mo^{101}	14.6 min		5.00	6.00	6.02	6.29	5.50	4.21
Tc^{101}	14.0 min	$a=1$	—	—	—	—	—	—
Ru^{103}	41 d		2.90	3.97	6.25	6.39	4.89	3.27
Rh^{103m}	57 min	$a=1$	—	—	—	—	—	—
Ru^{105}	4.5 h		0.90	1.02	4.68	4.36	3.53	1.75
Rh^{105m}	45 sec	$a=0.12$	—	—	—	—	—	—
Rh^{105}	36.5 h	$a=1$; $b=1$	—	—	—	—	—	—
Ru^{106}	1.0 y		0.38	0.47	6.17	2.61	3.11	1.40
Rh^{106}	30 sec	$a=1$	—	—	—	—	—	—
Rh^{107}	26 min		0.20	0.28	4.66	1.26	2.39	1.26
Pd^{109}	13.6 h		0.028	0.11	1.65	0.27	1.14	1.12
Ag^{109m}	39.2 sec	$a=1$	—	—	—	—	—	—
Pd^{111}	22 min		0.018	0.060	0.48	0.071	0.83	1.03
Ag^{111}	7.6 d	$a=1$	—	—	—	—	—	—
Pd^{112}	21 h		0.011	0.043	0.17	0.042	0.77	0.93
Ag^{112}	3.2 h	$a=1$	—	—	—	—	—	—
Ag^{113}	5.3 h		0.01	0.043	0.17	0.042	0.77	0.93
Cd^{113m}	5.1 y	$a=0.005$	—	—	—	—	—	—
Ag^{115}	20 min		0.01	0.045	0.073	0.039	0.70	0.92
Cd^{115m}	43 d	$a=1$	—	—	—	—	—	—
Cd^{115}	53 h	$a=1$	Ag^{115} (0.0098)	—	—	—	—	—
In^{115m}	4.5 h	$b=1$	Ag^{115} (0.0098)	—	—	—	—	—

Table 2 (cont.)

Nuclide	Half life	a, b, c, d*	U^{235}, n_{th}	U^{235}, n_f	Pu^{239}, n_f	U^{238}, n_f	U^{238}, n_{14}	U^{235}, n_{14}
Cd^{117m}	2.9 h		0.01	0.048	0.007	0.038	0.69	0.92
Cd^{117}	50 min	$a=0.8$	—	—	—	—	—	—
In^{117m}	1.9 h	$b=1$	—	—	—	—	—	—
In_1^{117}	1.1 h	$d=0.22$	—	—	—	—	—	—
In_2^{117}	1.1 h	$a=0.2$	from Cd^{117}	—	—	—	—	—
In^{119}	17.5 min		0.01	0.052	0.007	0.037	0.69	0.98
Sn^{123m}	125 d		0.0012	0.0042	0.010	0.004	0.06	0.10
Sn^{123}	39.5 min		0.014	0.049	0.119	0.041	0.75	1.18
Sn^{125}	9.4 d		0.012	0.064	0.134	0.026	0.52	0.71
Sb^{125}	2.0 y	$a=1$	0.011	0.059	0.123	0.024	0.48	0.65
Te^{125m}	58 d	$b=0.26$	—	—	—	—	—	—
Sb^{126m}	6.2 d		0.10	0.18	0.40	0.078	1.30	1.43
Sb^{126}	19 min	$a=1$	—	—	—	—	—	—
Sn^{127}	2.05 h		0.25	0.26	0.62	0.12	1.61	1.75
Sb^{127}	88 h	$a=1$	—	—	—	—	—	—
Te^{127m}	105 d	$b=0.20$	—	—	—	—	—	—
Te_1^{127}	9.3 h	$b=0.80$	from Sn^{127}	—	—	—	—	—
Te_2^{127}	9.3 h	$a=0.20$ $b=1$	from Sb^{127}	—	—	—	—	—
Sn^{128}	57 min		0.50	0.43	1.09	0.29	2.14	1.76
Sb^{128m}	9.6 h	$a=0.03$	—	—	—	—	—	0.47
Sb^{128}	10 min	$a=0.97$	—	—	—	—	—	—
Sb^{129}	4.6 h		0.90	0.79	1.78	0.88	2.80	2.62
Te^{129m}	33 d	$a=0.24$	—	—	—	—	—	—
Te^{129}	67 min	$b=0.95$ $c=0.76$	—	—	—	—	—	—
Sb^{130}	33 min		2.10	1.52	2.97	2.08	3.53	3.40
Sb^{131}	21 min		2.92	3.11	4.85	3.33	4.26	4.08
Te^{131m}	30 h	$a=0.15$	—	—	—	—	—	—
Te^{131}	24.8 min	$b=0.22$ $c=0.85$	—	—	—	—	—	—
I_1^{131}	8.05 d	$a=0.85$ $b=1$	from Sb^{131}	—	—	—	—	—
I_2^{131}	8.05 d	$a=b=d=1$	Sb^{131} (0.10)	—	—	—	—	—
I_3^{131}	8.05 d	$a=b=1$	Sb^{131} (0.34)	—	—	—	—	—
Xe^{131m}	12 d	$a=1$ $b=0.01$	Te^{131m} (0.44) I^{131} (2.48)	—	—	—	—	—
Te^{132}	77 h		4.37	4.44	6.32	4.89	4.89	4.80
I^{132}	2.26 h	$a=1$	—	—	—	—	—	—
Te^{133m}	53 min		4.60	4.26	4.38	4.05	5.19	3.81
Te^{133}	2 min	$a=0.13$	—	—	—	—	—	—
I^{133}	20.8 h	$a=1$	1.90	1.76	1.81	1.67	—	1.58
Xe^{133m}	2.3 d	$b=0.024$	—	—	—	—	—	—
Xe^{133}	5.27 d	$a=1$; $b=1$	—	—	—	—	—	—
Te^{134}	44 min		6.70	6.53	5.23	5.76	5.45	4.20
I^{134}	52.5 min	$a=1$	1.33	1.30	1.04	1.14	—	1.48
I^{135}	6.68 h		5.90	6.04	5.68	5.75	5.26	4.51
Xe^{135m}	15.6 min	$a=0.27$	—	—	—	—	—	0.93
Xe^{135}	9.13 h	$b=1$; $c=0.73$	0.50	0.51	0.48	0.49	0.45	—
Cs^{137}	26.6 y		6.15	6.18	6.14	6.45	5.71	5.10
Ba^{137m}	2.6 min	$a=0.92$	—	—	—	—	—	—
Xe^{138}	17 min		5.77	6.11	5.54	6.35	5.52	3.89
Cs^{138}	32 min	$a=1$	—	—	—	—	—	1.16

Table 2 (cont.)

Nuclide	Half life	a, b, c, d*	U^{235}, n_{th}	U^{235}, n_f	Pu^{239}, n_f	U^{238}, n_f	U^{238}, n_{14}	U^{235}, n_{14}
Ba^{139}	85 min		6.00	6.24	5.25	6.14	5.19	4.87
Ba^{140}	12.8 d		6.33	5.79	4.95	5.93	4.69	4.66
La^{140}	40.2 h	$a=1$	—	—	—	—	—	—
Ba^{141}	18 min		5.90	5.20	4.58	5.53	4.38	4.40
La^{141}	3.7 h	$a=1$	0.10	0.09	0.07	0.09	0.07	0.07
Ce^{141}	32 d	$b=1$	—	—	—	—	—	—
La^{142}	74 min		6.03	5.18	4.36	5.20	4.15	4.08
La^{143}	19 min		5.80	5.18	4.85	4.89	3.74	3.69
Ce^{143}	32 h	$a=1$	—	—	—	—	—	—
Ce^{144}	285 d		5.39	4.76	3.66	4.42	3.32	3.30
Pr^{144}	17.5 min	$a=1$	—	—	—	—	—	—
Pr^{145}	6.0 h		3.86	4.31	3.22	3.85	2.91	2.72
Ce^{146}	13.9 min		2.93	3.86	2.87	3.33	2.39	2.23
Pr^{146}	24.4 min	$a=1$	—	—	—	—	—	—
Nd^{147}	11.3 d		2.38	3.24	2.52	2.81	2.07	1.84
Nd^{149}	2.0 h		1.13	1.17	1.88	1.98	1.32	1.07
Pm^{149}	54 h	$a=1$	—	—	—	—	—	—
Nd^{151}	12 min		0.45	0.46	1.29	0.94	0.83	0.55
Pm^{151}	27.5 h	$a=1$	—	—	—	—	—	—
Sm^{153}	47 h		0.15	0.14	0.48	0.40	0.40	0.24
Sm^{155}	23.5 min		0.031	0.029	0.18	0.11	0.21	0.09
Eu^{155}	1.7 y	$a=1$	—	—	—	—	—	—
Sm^{156}	10 h		0.013	0.013	0.08	0.07	0.11	0.05
Eu^{156}	15.4 d	$a=1$	—	—	—	—	—	—

* *Note:* a denotes the fraction of nuclide 1 decaying to nuclide 2.
b denotes the fraction of nuclide 2 decaying to nuclide 3.
c denotes the fraction of nuclide 1 decaying to nuclide 3.
d denotes the fraction of nuclide 3 decaying to nuclide 4.

fission products are still uncertain. These lines have been estimated very roughly by Miller [38] who gives Rb^{91m} 1.2 MeV γ (100 %), Pd^{111} 0.65 (60), 0.73 (60), Cd^{117m} 0.28 (80), 1.27 (80), 1.53 (20) and Sn^{127} 0.5 (100), and Perkins and King [18], Y^{95} 0.9 (100), Sb^{131} 1.02 (100) and La^{143} 1.5 (5). As will be shown later, these values are most probably not accurate, yet they have been used to simplify comparisons.

Besides thermal neutron fission of U^{235} a number of alternatives are considered. Fission of three nuclides, U^{235}, Pu^{239} and U^{238}, with fission neutrons (n_f) is calculated as well as 14 MeV neutron (n_{14}) fission of U^{238} and U^{235}. The chain yield values have been taken from an extensive literature survey made by Prawitz [48].

The initial yields determined in thermal neutron fission of U^{235} have mostly been used, corrected to the corresponding chain yields, to describe the five other fission modes that are calculated. This is possible as the most probable charge in a chain often does not change too much from one fission mode to another. In those cases where the most probable charge is displaced more than one mass number from that in (U^{235}, n_{th}), and this change occurs in a region of independent yields, new yield values have been calculated. This has been the case with (U^{235}, n_{14}) for the nuclides Nb^{97}, Sb^{128m}, I^{134}, Xe^{135m}, and Cs^{138} and with (U^{238}, n_{14}) for Xe^{133m}, Xe^{133}, I^{133}, and I^{134}. Values on the most stable charge have been taken from Grummit and Milton [49] and the distribution of most probable charge was taken from Wahl [34]. All yield values used have been tabulated in table 2.

Table 3. Results.

Time	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
1 hour													
U^{235}, n_{th}	2.14–1	6.70	2.05	5.70	11.7	2.66	7.49	2.02	12.0	1.48	7.68	1.64	2.63
U^{235}, n_f	2.11–1	7.15	2.11	6.57	12.7	2.79	6.90	2.21	11.2	1.48	7.48	1.66	2.39
Pu^{239}, n_f	3.34–1	8.43	2.07	9.59	10.7	2.80	6.61	3.19	10.0	1.22	7.26	1.54	1.30
U^{238}, n_f	2.70–1	7.73	2.23	7.30	11.7	2.74	6.58	2.65	10.5	1.28	7.12	1.56	1.77
U^{238}, n_{14}	3.71–1	8.11	2.01	8.96	11.2	3.24	7.05	3.71	9.72	1.23	7.50	1.38	1.80
U^{235}, n_{14}	3.42–1	7.89	1.95	7.06	10.1	3.26	6.54	3.05	10.3	1.36	7.05	1.35	2.38
2 hours	1.77–1	2.83	1.01	1.06	4.36	1.25	4.30	1.26	8.05	4.24–1	2.87	1.05	4.44–1
	1.62–1	2.91	9.84–1	1.10	4.58	1.21	4.01	1.30	7.71	3.95–1	2.76	1.04	4.38–1
	2.77–1	3.38	1.03	2.06	3.96	1.21	3.73	2.30	6.50	3.26–1	2.56	9.23–1	3.66–1
	2.00–1	3.22	1.07	1.34	4.26	1.07	3.81	1.91	6.99	3.46–1	2.61	9.51–1	3.90–1
	3.65–1	3.37	1.05	2.22	4.39	1.58	3.92	2.32	6.41	3.96–1	2.70	8.61–1	5.24–1
	3.52–1	3.36	1.02	1.76	4.10	1.66	3.56	1.75	6.20	4.61–1	2.38	8.01–1	5.68–1
5 hours	1.39	7.20	6.77	1.87	6.28	8.44	10.7	6.79	15.3	3.09	4.96	3.81	2.26
× 10	1.26	7.14	6.56	1.80	6.29	7.91	10.4	6.94	15.0	2.77	4.65	3.82	2.33
	2.21	7.92	6.81	3.71	6.03	7.44	9.60	10.3	12.6	2.12	3.82	3.44	2.27
	1.44	8.41	6.89	2.77	6.51	6.79	9.80	9.94	13.4	2.38	4.05	3.54	2.22
	3.10	8.85	6.74	4.56	7.58	9.10	10.2	9.61	13.2	2.62	4.33	3.28	2.91
	3.00	9.12	6.43	3.95	7.46	9.78	9.20	7.16	11.9	3.11	4.03	2.92	2.86
10 hours	8.93–1	2.69	5.69	8.45–1	1.56	6.15	4.64	4.95	1.74	1.82	1.60	1.72	1.35
× 10	8.19–1	2.67	5.56	8.36–1	1.52	5.74	4.73	5.06	1.68	1.61	1.48	1.74	1.38
	1.33	3.19	5.61	1.80	1.93	5.14	4.43	6.26	1.83	1.28	1.07	1.68	1.34
	8.77–1	3.19	5.58	1.42	1.92	5.00	4.33	6.21	1.68	1.40	1.17	1.66	1.32
	1.73	3.70	5.25	1.99	2.21	5.55	4.70	5.78	2.05	1.50	1.24	1.57	1.52
	1.68	3.71	5.16	1.75	2.14	5.98	4.23	4.61	1.94	1.76	1.38	1.41	1.41
1 day	4.83	11.9	34.1	3.36	3.48	29.0	25.9	25.8	4.22	3.64	5.14	5.37	3.39
$\times 10^2$	4.56	12.0	33.8	3.48	3.55	27.1	26.7	26.3	3.88	3.33	4.75	5.41	3.44
	5.56	13.6	34.6	7.03	5.05	24.8	25.4	25.7	4.31	3.29	3.07	5.64	3.31
	4.56	13.0	33.2	5.53	4.33	24.2	24.0	25.3	3.99	3.13	3.64	5.24	3.27
	5.43	13.6	30.5	7.01	5.55	25.6	26.3	25.1	4.23	3.31	3.54	5.15	3.20
	5.29	12.0	29.5	6.35	5.37	27.9	23.8	22.7	3.89	3.83	4.15	4.69	2.83
2 days	3.89	8.65	12.8	2.27	1.61	10.9	12.0	11.4	1.79	1.25	9.48–1	1.43	4.22–1
$\times 10^2$	3.78	8.66	12.7	2.38	1.72	10.3	12.4	11.7	1.67	1.23	8.78–1	1.42	4.17–1
	4.09	9.11	14.2	4.34	2.46	10.2	13.1	11.8	1.58	1.57	5.54–1	1.74	4.01–1
	3.72	8.96	12.8	3.38	1.98	9.65	11.7	10.9	1.59	1.29	6.66–1	1.44	3.94–1
	3.50	8.83	11.9	4.06	2.94	9.08	12.9	11.3	1.39	1.36	6.29–1	1.52	3.67–1
	3.48	7.56	11.6	3.79	3.02	9.48	12.0	10.7	1.34	1.57	7.45–1	1.46	3.35–1
5 days	2.42	4.04	2.87	1.45	1.16	1.87	2.99	3.11	7.35–1	6.46–1	1.76–2	3.52–1	1.52–2
$\times 10^2$	2.48	4.00	2.84	1.51	1.23	1.83	3.10	3.17	6.73–1	6.43–1	1.77–2	3.51–1	1.43–2
	2.49	3.92	3.80	2.33	1.56	2.02	4.26	3.81	5.98–1	8.32–1	1.67–2	4.66–1	1.42–2
	2.33	4.07	3.04	1.80	1.43	1.85	3.28	3.19	6.75–1	6.88–1	1.51–2	3.66–1	1.34–2
	2.16	3.88	3.06	2.22	1.83	1.75	3.88	3.36	5.44–1	7.25–1	2.09–2	4.00–1	1.24–2
	2.14	3.32	3.00	2.21	1.85	1.76	3.81	3.50	5.39–1	8.36–1	2.29–2	3.94–1	1.25–2
10 days	12.8	14.3	8.05	9.22	8.96	6.44	9.54	12.7	4.92	3.15	3.60–3	7.61–1	2.62–3
$\times 10^3$	12.8	13.8	8.19	9.48	9.57	6.49	10.0	13.0	4.50	3.07	8.34–3	7.76–1	2.43–3
	13.0	12.8	11.5	13.1	11.4	6.79	14.7	14.6	3.86	3.60	2.63–2	1.09	2.48–3
	12.4	14.1	8.85	10.2	11.5	6.67	10.8	12.6	4.60	3.23	9.27–3	8.23–1	2.30–3
	11.5	12.8	9.39	12.2	11.9	5.90	14.0	12.9	3.66	3.32	5.45–2	9.81–1	2.12–3
	11.3	11.2	9.24	12.4	11.2	5.76	14.0	14.0	3.63	3.79	6.77–2	9.83–1	2.16–3

Table 3 (cont.)

Time	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
1 hour												
U^{235}, n_{th}	2.08	4.87	4.94–1	6.37–1	6.28–1	1.10	9.31–2	9.64–1	2.22–1	1.11	1.00–7	1.54
U^{235}, n_f	1.84	5.33	5.00–1	5.96–1	6.48–1	1.04	5.41–2	8.88–1	2.13–1	1.14	1.23–7	1.36
Pu^{239}, n_f	1.20	4.62	3.56–1	4.64–1	6.23–1	7.06–1	1.89–2	7.36–1	7.72–2	9.27–1	1.62–6	9.35–1
U^{238}, n_f	1.52	5.30	4.35–1	5.40–1	6.61–1	8.88–1	6.94–2	9.03–1	1.47–1	1.12	6.87–7	1.24
U^{238}, n_{14}	1.37	4.45	4.15–1	4.46–1	6.50–1	7.50–1	7.49–2	7.66–1	1.33–1	9.80–1	8.18–7	1.02
U^{235}, n_{14}	1.65	3.88	4.78–1	4.77–1	5.13–1	9.00–1	1.20–1	7.72–1	2.26–1	9.05–1	3.68–7	1.20
2 hours	15.4	18.5	1.53	2.35	2.21	8.24	3.29–1	4.12	1.70	3.42	1.00–6	9.52
× 10	13.3	19.8	1.52	2.27	2.22	7.88	2.12–1	3.58	1.66	3.59	1.23–6	8.53
	8.34	17.1	6.71–1	1.80	2.35	5.25	9.96–2	2.80	6.03–1	3.18	1.62–5	5.64
	10.7	19.5	1.09	2.01	2.19	6.60	2.47–1	3.54	1.12	3.67	6.87–6	7.42
	9.60	16.6	1.29	1.71	2.54	5.69	2.59–1	2.93	1.02	3.22	8.18–6	6.27
	11.8	14.3	1.93	1.63	2.21	6.64	3.96–1	3.12	1.71	2.71	3.68–6	7.55
5 hours	7.23	2.61	5.92–1	4.23–1	1.35	2.93	1.13–1	6.98–1	8.09–1	1.34–1	1.00–6	2.65
× 10	6.28	2.47	5.92–1	4.16–1	1.36	2.85	9.98–2	6.12–1	7.90–1	1.40–1	1.23–6	2.46
	3.99	1.90	2.08–1	3.34–1	1.46	1.80	8.12–2	4.82–1	2.95–1	1.26–1	1.62–5	1.36
	5.09	2.16	3.96–1	3.66–1	1.31	2.31	8.89–2	5.95–1	5.34–1	1.36–1	6.87–6	1.98
	4.56	1.94	5.15–1	3.40–1	1.56	2.07	8.40–2	4.82–1	4.91–1	1.26–1	8.18–6	1.68
	5.58	1.99	8.16–1	2.94–1	1.37	2.50	9.90–2	5.04–1	8.17–1	1.04–1	3.68–6	2.28
10 hours	21.9	13.6	1.70	8.45–1	7.91	9.16	8.35–1	4.22–1	2.52	5.38–1	1.00–5	5.05
× 10^2	19.2	12.6	1.70	8.41–1	7.99	9.02	7.66–1	3.72–1	2.44	5.61–1	1.23–5	4.86
	12.7	9.43	5.97–1	7.01–1	8.34	6.08	7.16–1	2.92–1	9.80–1	5.12–1	1.62–4	2.04
	15.8	10.7	1.14	7.63–1	7.70	7.46	7.04–1	3.59–1	1.68	4.99–1	6.87–5	3.46
	14.4	9.72	1.50	8.17–1	8.73	6.84	6.72–1	2.91–1	1.63	5.06–1	8.18–5	3.06
	17.2	10.6	2.37	7.60–1	7.66	8.00	7.46–1	3.05–1	2.61	4.37–1	3.68–5	4.82
1 day	1.92	3.28	5.11–2	9.28–1	1.88	1.46	3.35–1	1.83–5	2.03–1	3.46–1	1.00–5	1.39–1
× 10^2	1.83	3.11	5.12–2	8.85–1	1.92	1.43	3.32–1	2.11–5	1.83–1	3.60–1	1.23–5	1.35–1
	1.55	2.65	1.84–2	7.54–1	1.88	1.21	4.37–1	5.78–6	1.20–1	3.51–1	1.62–4	5.08–2
	1.60	2.74	3.46–2	8.59–1	1.82	1.30	3.56–1	1.32–5	1.45–1	3.29–1	6.87–5	9.16–2
	1.71	2.55	4.81–2	8.15–1	1.87	1.24	3.60–1	1.29–5	2.17–1	3.33–1	8.18–5	8.26–2
	1.75	2.71	7.50–2	7.94–1	1.64	1.23	3.57–1	2.34–5	2.81–1	2.94–1	3.68–5	1.37–1
2 days	5.43	7.66	1.51–3	12.0	1.96	1.62	2.23		3.14–1	1.77	9.98–5	4.58–3
× 10^3	5.37	7.52	1.58–3	11.2	2.02	1.51	2.27		2.81–1	1.83	1.22–4	4.33–3
	5.06	8.72	4.51–3	9.50	1.83	1.30	3.33		2.69–1	2.00	1.62–3	1.86–3
	4.81	7.48	2.57–3	11.2	1.85	1.38	2.59		2.44–1	1.76	6.85–4	3.05–3
	5.61	7.28	3.36–3	9.45	1.81	1.54	2.69		6.17–1	1.78	8.17–4	2.74–3
	5.49	7.47	2.95–3	9.33	1.54	1.61	2.55		7.42–1	1.62	3.68–4	4.27–3
5 days	4.05–1	2.54	2.48–4	15.3	3.17–2	8.93–3	1.16		1.09–2	5.05–1	9.92–5	
× 10^3	3.98–1	2.57	3.04–4	14.1	3.33–2	8.79–3	1.18		1.13–2	5.16–1	1.22–4	
	4.01–1	3.65	4.03–3	12.0	2.74–2	1.14–2	1.78		1.63–2	7.01–1	1.61–3	
	3.58–1	2.83	1.70–3	14.3	2.83–2	7.75–3	1.39		1.07–2	5.54–1	6.81–4	
	4.80–1	2.83	2.03–3	11.4	2.89–2	3.50–2	1.47		4.64–2	5.55–1	8.12–4	
	4.89–1	2.79	9.14–4	11.4	2.36–2	4.20–2	1.36		5.44–2	5.38–1	3.65–4	
10 days	8.52–3	8.60–1	2.46–4	13.6	3.35–4	7.77–6	4.06–1		7.05–3	1.56–1	9.84–5	
× 10^3	1.03–2	8.75–1	3.02–4	12.4	3.70–4	3.32–5	4.15–1		6.27–3	1.59–1	1.21–4	
	1.61–2	1.24	3.99–3	10.6	1.79–3	1.27–4	6.66–1		5.72–3	2.25–1	1.60–3	
	7.33–3	9.61–1	1.69–3	12.7	8.83–4	3.18–5	5.22–1		6.11–3	1.75–1	6.76–4	
	4.00–2	9.63–1	2.01–3	10.1	1.02–3	5.65–4	5.87–1		5.47–3	1.75–1	8.05–4	
	4.38–2	9.45–1	9.06–4	10.0	5.37–4	6.78–4	5.13–1		5.37–3	1.71–1	3.63–4	

Table 3 (cont.)

Time	2.5	2.6	2.7	2.8	2.9	3.0	3.2	3.4	3.5	3.6	3.9	4.8
1 hour × 10												
U^{235}, n_{th}	4.79	4.73	4.35–1	1.13–1	2.90	2.13–1	1.77–1	9.66–1	3.12–1	1.12–2	6.14–1	3.36–2
U^{235}, n_f	4.97	4.98	3.78–1	6.37–2	2.49	1.34–1	1.14–1	8.30–1	2.74–1	1.10–2	3.46–1	3.31–2
Pu^{239}, n_f	1.50	4.38	1.31–1	1.99–2	2.09	4.33–2	3.70–2	6.97–1	9.51–2	3.92–3	1.08–1	1.18–2
U^{238}, n_f	3.20	5.09	2.56–1	8.42–2	2.50	1.55–1	1.29–1	8.33–1	1.86–1	7.36–3	4.57–1	2.21–2
U^{238}, n_{14}	3.04	4.43	2.28–1	9.14–2	2.00	1.65–1	1.36–1	6.65–1	1.64–1	6.63–3	4.97–1	1.99–2
U^{235}, n_{14}	5.31	3.88	3.75–1	1.49–1	1.96	2.70–1	2.22–1	6.54–1	2.72–1	1.13–2	8.09–1	3.39–2
2 hours	1.85	1.84	2.91–2	3.21–2	1.66	8.02–2	7.01–2	5.52–1	3.91–2	9.84–3	1.74–1	2.95–2
× 10	2.08	1.92	2.54–2	1.81–2	1.43	5.76–2	5.19–2	4.74–1	3.62–2	9.68–3	9.81–2	2.90–2
	6.01–1	1.62	9.10–3	5.65–3	1.20	1.92–2	1.74–2	3.99–1	1.27–2	3.44–3	3.06–2	1.03–2
	1.32	1.92	1.72–2	2.39–2	1.43	5.72–2	4.96–2	4.76–1	2.43–2	6.46–3	1.30–1	1.94–2
	1.29	1.67	1.67–2	2.60–2	1.14	5.85–2	5.03–2	3.80–1	2.18–2	5.83–3	1.41–1	1.75–2
	2.29	1.49	2.68–2	4.23–2	1.12	9.65–2	8.32–2	3.74–1	3.66–2	9.92–3	2.29–1	2.97–2
5 hours	3.74	1.49	3.63–4	7.33–3	3.06	1.54–1	1.51–1	1.02	9.44–2	4.72–2	3.98–2	1.42–1
× 10^2	4.27	1.49	1.55–3	4.13–3	2.63	1.47–1	1.45–1	8.76–1	9.29–2	4.64–2	2.24–2	1.40–1
	1.37	7.41–1	5.94–3	1.29–3	2.21	5.17–2	5.13–2	7.36–1	3.30–2	1.65–2	7.00–3	4.97–2
	2.75	1.14	1.49–3	5.46–3	2.64	1.02–1	1.00–1	8.79–1	6.20–2	3.10–2	2.97–2	9.33–2
	2.77	1.02	2.64–2	5.93–3	2.11	9.35–2	9.16–2	7.02–1	5.59–2	2.79–2	3.22–2	8.41–2
	4.65	1.45	3.17–2	9.66–3	2.07	1.58–1	1.55–1	6.91–1	9.52–2	4.76–2	5.25–2	1.43–1
10 hours	5.34	3.26	4.31–3	1.35–4	1.85	4.05–1	4.05–1	6.15–1	2.70–1	1.35–1	7.29–4	4.05–1
× 10^3	5.85	3.21	1.84–2	7.61–5	1.59	3.99–1	3.99–1	5.28–1	2.66–1	1.33–1	4.11–4	3.99–1
	3.31	1.14	7.05–2	2.38–5	1.34	1.42–1	1.42–1	4.44–1	9.45–2	4.72–2	1.28–4	1.42–1
	4.35	2.14	1.76–2	1.01–4	1.60	2.66–1	2.66–1	5.30–1	1.77–1	8.87–2	5.43–4	2.66–1
	4.92	1.95	3.13–1	1.09–4	1.28	2.40–1	2.40–1	4.23–1	1.60–1	7.99–2	5.90–4	2.40–1
	5.94	3.32	3.76–1	1.78–4	1.26	4.08–1	4.08–1	4.16–1	2.72–1	1.36–1	9.61–4	4.08–1
1 day	1.98	9.77–2	3.19–3		1.57–2	1.22–2	1.22–2		8.14–3	4.07–3		1.22–2
× 10^3	2.05	9.61–2	1.36–2		1.44–2	1.20–2	1.20–2		8.01–3	4.00–3		1.20–2
	1.70	3.45–2	5.22–2		1.23–2	4.27–3	4.27–3		2.85–3	1.42–3		4.27–3
	1.77	6.43–2	1.31–2		1.47–2	8.02–3	8.02–3		5.35–3	2.67–3		8.02–3
	2.16	5.80–2	2.32–1		1.16–2	7.22–3	7.22–3		4.82–3	2.41–3		7.22–3
	2.01	9.88–2	2.78–1		1.16–2	1.23–2	1.23–2		8.21–3	4.10–3		1.23–2
2 days	12.3	2.60–3	1.46–2		2.52–1	3.00–4	3.00–4		2.00–4	1.00–4		3.00–4
× 10^4	12.1	2.60–3	6.24–2		2.31–1	2.95–4	2.95–4		1.97–4	9.84–5		2.95–4
	10.3	4.09–3	2.39–1		1.97–1	1.05–4	1.05–4		7.00–5	3.50–5		1.05–4
	11.2	2.95–3	5.97–2		2.36–1	1.97–4	1.97–4		1.31–4	6.57–5		1.97–4
	12.1	3.06–3	1.06		1.87–1	1.78–4	1.78–4		1.18–4	5.92–5		1.78–4
	11.6	3.16–3	1.27		1.85–1	3.02–4	3.02–4		2.02–4	1.01–4		3.02–4
5 days	9.02	1.98–4	1.36–3		3.48–1							
× 10^4	8.30	2.43–4	5.81–3		3.18–1							
	7.10	3.21–3	2.23–2		2.72–1							
	8.44	1.36–3	5.56–3		3.26–1							
	6.93	1.62–3	9.89–2		2.58–1							
	6.87	7.29–4	1.19–1		2.56–1							
10 days	7.75	1.97–4	2.59–5		3.10–1							
× 10^4	7.09	2.42–4	1.11–4		2.84–1							
	6.06	3.20–3	4.24–4		2.42–1							
	7.26	1.35–3	1.06–4		2.90–1							
	5.75	1.61–3	1.88–3		2.30–1							
	5.71	7.26–4	2.26–3		2.28–1							

Table 3 (cont.)

Time	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1
30 days × 10^3												
U^{235}, n_{th}	2.00	2.82	2.41–1	2.07	3.90	1.47	4.50–1	5.39	1.67	5.64–1	1.01–3	2.12–2
U^{235}, n_f	2.09	2.51	2.61–1	2.08	4.43	1.46	5.36–1	5.66	1.53	5.21–1	2.25–3	2.12–2
Pu^{239}, n_f	2.07	2.21	3.45–1	2.59	5.62	1.40	8.88–1	4.41	1.32	4.64–1	1.51–2	2.58–2
U^{238}, n_f	2.06	2.64	2.74–1	2.17	5.97	1.51	6.66–1	4.68	1.56	5.32–1	5.75–3	1.85–2
U^{238}, n_{14}	2.02	2.12	3.13–1	2.34	4.81	1.23	9.64–1	4.03	1.25	4.64–1	1.71–2	3.71–2
U^{235}, n_{14}	1.90	2.11	2.96–1	2.28	3.81	1.15	8.89–1	4.45	1.24	4.80–1	1.78–2	4.01–2
100 days × 10^4	8.59–1	6.00	2.21–1	2.50–1	6.09	4.18–1	8.21–1	37.1	3.80–1	1.22–1	6.68–3	4.81–2
	8.15–1	5.30	2.43–1	2.37–1	8.13	4.55–1	9.74–1	38.9	3.49–1	1.12–1	8.38–3	4.33–2
	1.11	4.62	2.42–1	2.27–1	12.5	1.70	1.96	29.7	3.36–1	9.55–2	1.07–1	3.90–2
	8.72–1	5.54	2.37–1	2.45–1	12.8	9.35–1	1.57	32.0	3.71–1	1.14–1	4.57–2	3.62–2
	1.42	4.45	2.47–1	2.18–1	10.1	1.13	1.41	27.2	3.00–1	9.07–2	5.76–2	4.12–2
	1.30	4.46	2.47–1	2.16–1	7.11	8.00–1	9.72–1	29.9	2.87–1	9.02–2	2.97–2	4.64–2
1 year × 10^5	1.55	5.05	1.02–1	2.19–3	6.83–1	5.40–1	3.39	27.4	1.51–2		4.03–2	2.40–2
	1.37	4.49	1.27–1	9.37–3	1.12	7.90–1	3.44	28.8	1.85–2		4.97–2	2.31–2
	1.23	3.61	1.33–1	1.94–2	1.89	8.51	7.54	21.9	2.45–1		6.54–1	9.03–2
	1.35	4.22	9.88–2	4.41–3	1.50	3.53	5.09	23.7	1.04–1		2.76–1	4.64–2
	1.23	3.56	2.67–1	7.24–2	3.10	5.48	5.34	20.1	1.24–1		3.36–1	5.22–2
	1.12	3.59	3.39–1	9.77–2	3.47	3.71	3.96	22.1	5.56–2		1.58–1	3.35–2
3 years × 10^6	2.76	8.66	2.19–2	8.12–3	2.32–1	1.41	25.1	9.00–2	3.76–2		1.00–1	1.25–2
	2.47	7.81	1.16–1	4.33–2	1.24	2.37	25.4	9.44–2	4.61–2		1.23–1	1.53–2
	2.59	6.68	2.41–1	9.05–2	2.59	22.0	35.7	7.20–2	6.10–1		1.62	2.03–1
	2.63	7.36	4.73–2	1.76–2	5.04–1	8.92	30.1	7.76–2	2.58–1		6.87–1	8.58–2
	2.77	7.43	9.39–1	3.52–1	10.1	17.0	29.7	6.60–2	3.08–1		8.19–1	1.02–1
	2.36	7.69	1.28	4.79–1	13.7	13.9	24.9	7.24–2	1.39–1		3.70–1	4.60–2
10 years × 10^6	1.37–2	2.67–2	1.91–3	7.16–4	2.05–2	4.27–2	19.4		2.94–4		7.84–4	9.80–5
	1.51–2	3.88–2	1.02–2	3.83–3	1.10–1	1.02–1	19.5		3.60–4		9.61–4	1.20–4
	5.26–2	7.60–2	2.13–2	8.00–3	2.29–1	3.18–1	19.5		4.77–3		1.27–2	1.59–3
	3.20–2	3.87–2	4.15–3	1.56–3	4.46–2	1.07–1	20.4		2.02–3		5.38–3	6.73–4
	7.86–2	1.87–1	8.30–2	3.11–2	8.91–1	6.97–1	18.2		2.41–3		6.42–3	8.02–4
	5.88–2	2.21–1	1.13–1	4.23–2	1.21	8.80–1	16.3		1.08–3		2.89–3	3.61–4
30 years × 10^6	2.68–6	4.55–6	1.86–6	6.98–7	2.00–5	4.97–3	11.6					
	5.00–6	1.86–5	9.95–6	3.73–6	1.07–4	4.40–3	11.7					
	1.84–5	4.38–5	2.08–5	7.80–6	2.23–4	1.38–3	11.6					
	8.72–6	1.17–5	4.04–6	1.52–6	4.35–5	2.47–3	12.2					
	3.89–5	1.51–4	8.09–5	3.03–5	8.70–4	4.94–3	10.8					
	3.95–5	1.97–4	1.10–4	4.13–5	1.18–3	7.93–3	9.62					
100 years × 10^6						4.39–5	1.86					
						3.83–5	1.87					
						1.08–5	1.86					
						2.16–5	1.95					
						3.85–5	1.73					
						6.31–5	1.54					

Table 3 (cont.)

Time	1.3	1.4	1.5	1.6	1.7	1.9	2.1	2.2	2.3	2.5	2.6	2.9
30 days × 10^3												
U^{235}, n_{th}	2.76–4	1.38–2	2.36–4	4.75	9.46–5	1.18–2	6.71–3	2.06–3	9.46–5	2.70–1	1.89–5	1.08–2
U^{235}, n_f	5.10–4	1.38–2	2.89–4	4.35	1.16–4	1.22–2	5.94–3	2.10–3	1.16–4	2.47–1	2.32–5	9.88–3
Pu^{239}, n_f	1.11–3	1.81–2	3.83–3	3.71	1.54–3	4.85–2	5.30–3	2.98–3	1.54–3	2.11–1	3.07–4	8.45–3
U^{238}, n_f	2.30–4	1.47–2	1.62–3	4.45	6.50–4	4.07–2	5.78–3	2.31–3	6.50–4	2.53–1	1.30–4	1.01–2
U^{238}, n_{14}	3.55–2	1.46–2	1.93–3	3.52	7.74–4	6.44–2	4.49–3	2.31–3	7.74–4	2.00–1	1.55–4	8.00–3
U^{235}, n_{14}	3.93–2	1.45–2	8.69–4	3.50	3.49–4	3.65–2	4.25–3	2.26–3	3.49–4	1.99–1	6.96–5	7.95–3
100 days	1.08–5	2.11–1	2.07–2	10.7	8.28–3	3.20–2	5.67–1		8.28–3	6.10–1	1.66–3	2.44–2
× 10^5	1.94–5	1.86–1	2.54–2	9.79	1.02–2	3.31–2	5.02–1		1.02–2	5.58–1	2.04–3	2.23–2
	4.28–5	1.43–1	3.36–1	8.37	1.34–1	2.37–1	4.50–1		1.34–1	4.77–1	2.69–2	1.91–2
	8.42–6	1.73–1	1.42–1	10.0	5.69–2	1.76–1	4.90–1		5.69–2	5.72–1	1.14–2	2.29–2
	1.40–4	1.30–1	1.69–1	7.93	6.78–2	2.71–1	3.81–1		6.78–2	4.52–1	1.36–2	1.81–2
	1.54–4	1.29–1	7.63–2	7.88	3.05–2	1.29–1	3.60–1		3.05–2	4.49–1	6.12–3	1.80–2
1 year		11.2	1.26		5.02–1	2.51–1	30.2		5.02–1		1.00–1	
× 10^7		9.89	1.54		6.15–1	3.08–1	26.7		6.15–1		1.23–1	
		7.62	20.5		8.15	4.07	24.4		8.15		1.62	
		9.18	8.65		3.45	1.72	26.2		3.45		6.87–1	
		6.90	10.3		4.11	2.05	20.4		4.11		8.18–1	
		6.85	4.64		1.85	9.25–1	19.2		1.85		3.68–1	
3 years		1.97	3.14–1		1.25–1	6.27–2	5.32		1.25–1		2.51–2	
× 10^7		1.74	3.85–1		1.53–1	7.69–2	4.72		1.53–1		3.08–2	
		1.34	5.10		2.03	1.02	4.60		2.03		4.07–1	
		1.62	2.16		8.58–1	4.31–1	4.74		8.58–1		1.72–1	
		1.21	2.57		1.02	5.13–1	3.75		1.02		2.05–1	
		1.21	1.16		4.60–1	2.31–1	3.45		4.60–1		9.25–2	
10 years		4.36	2.45		9.80–1	4.90–1	12.1		9.80–1		1.96–1	
× 10^{10}		3.85	3.00		1.20	6.01–1	10.8		1.20		2.40–1	
		2.96	39.8		15.9	7.95	15.8		15.9		3.18	
		3.58	16.8		6.73	3.37	12.9		6.73		1.35	
		2.69	20.1		8.02	4.01	11.2		8.02		1.60	
		2.67	9.03		3.61	1.81	8.91		3.61		7.22–1	

Results

γ-spectra given as number of γ-quanta per minute and 0.1 MeV energy interval for 10^4 fissions have been calculated for the following times after fission: hours: 1, 2, 5, 10; days: 1, 2, 5, 10, 30, 100; years: 1, 3, 10, 30, 100. 50 energy groups have been used, covering the range 0.0–5.0 MeV. Each group has a width of 100 keV from e.g. 1.300–1.399 MeV (denoted by 1.3 MeV). The results are summarized in tables 3, 4 and figs 1–4. Similar results giving spectra in terms of MeV/min and 10^4 fissions and with the same energy groups have been derived as well but are not given here [50].

The difference between (U^{235}, n_{th}) and other fission modes has been analyzed in two ways. Firstly the sum of γ-quanta per minute as a function of time after fission is expressed as percentage deviation from (U^{235}, n_{th}) in fig 5. Secondly the average γ-energy ($\Sigma \mathrm{MeV}/\Sigma\gamma$) has been calculated for all six modes and drawn in fig. 6. For thermal neutron fission of U^{235} the ratio β/γ varies as shown in fig. 7.

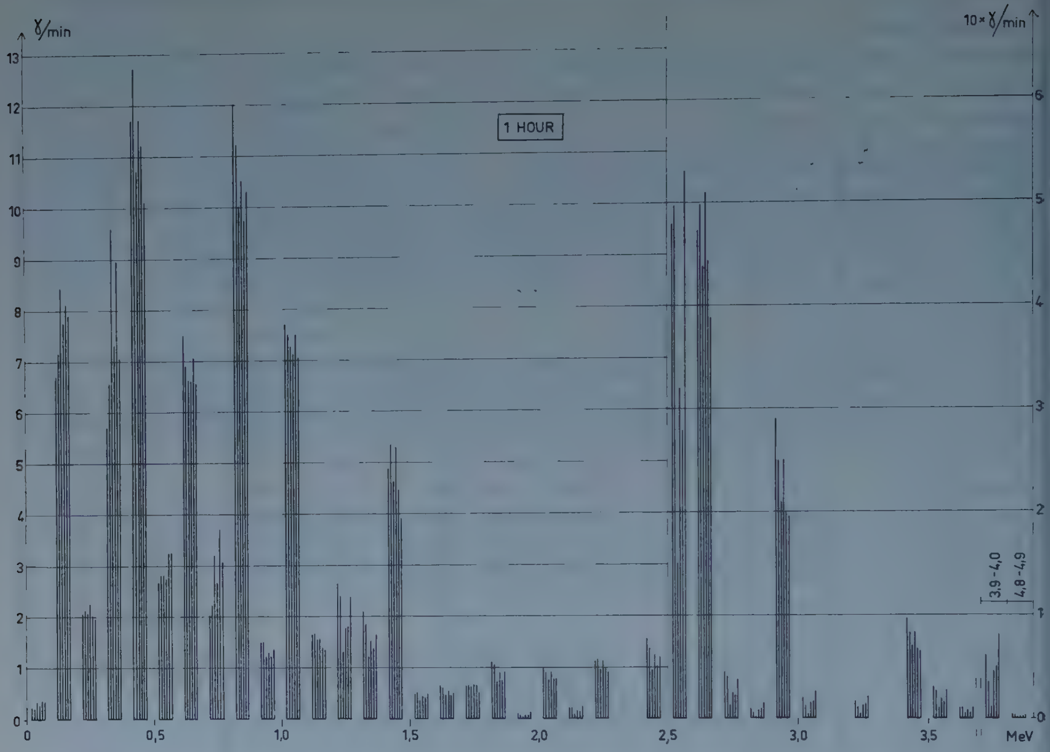

Fig. 1. γ-spectra at one hour after 10^4 simultaneous fissions. In each 0.1 MeV energy group six lines are shown corresponding to the number of γ-quanta in six alternative fission modes, from left to right (U^{235}, n_{th}); (U^{235}, n_f); (Pu^{239}, n_f); (U^{238}, n_f); (U^{238}, n_{14}) and (U^{235}, n_{14}).

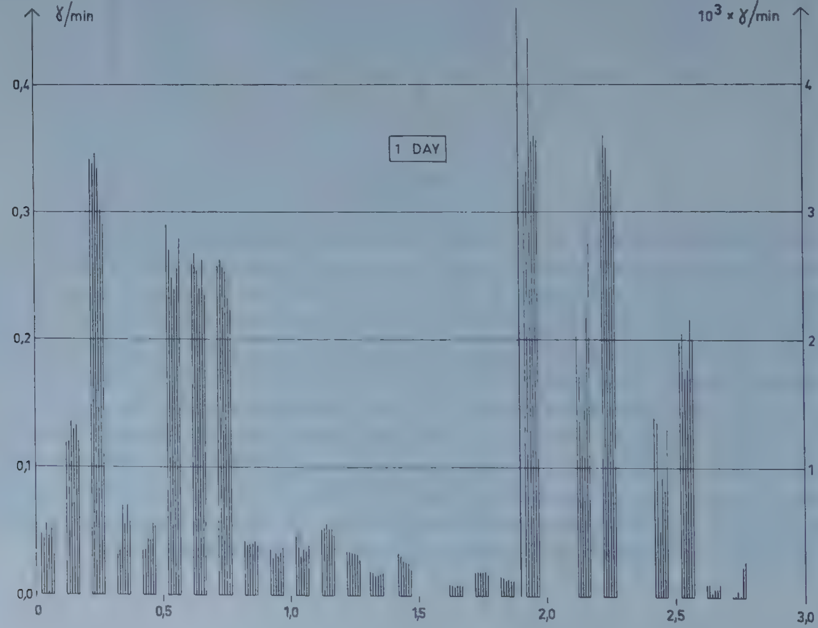

Fig. 2. γ-spectra at one day after 10^4 fissions. For notation see fig. 1.

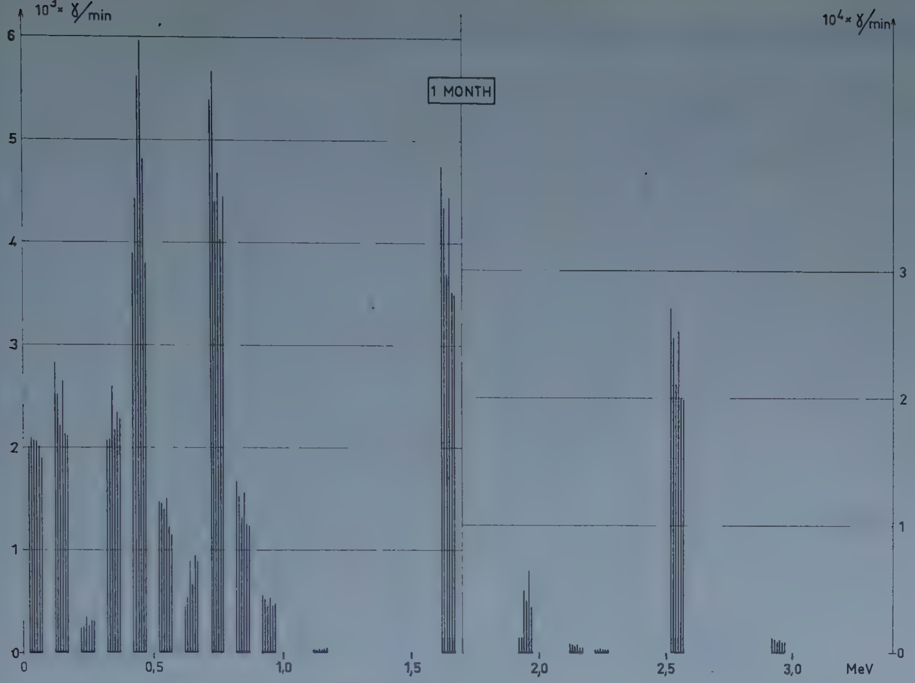

Fig. 3. γ-spectra at one month after 10^4 fissions. For notation see fig. 1.

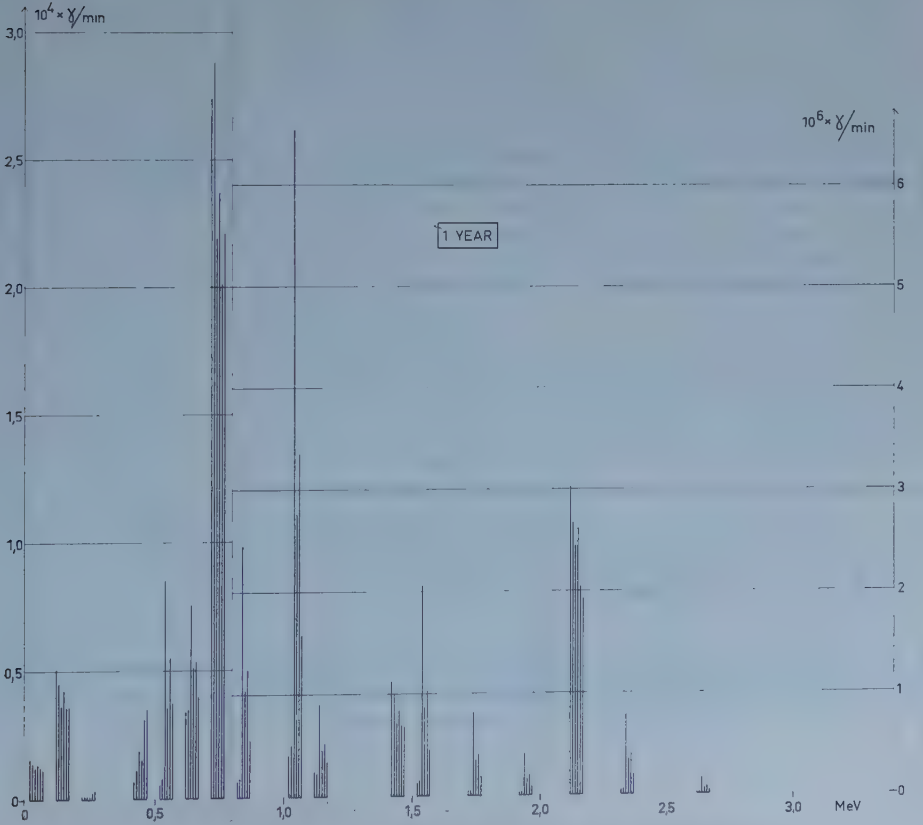

Fig. 4. γ-spectra at one year after 10^4 fissions. For notation see fig. 1.

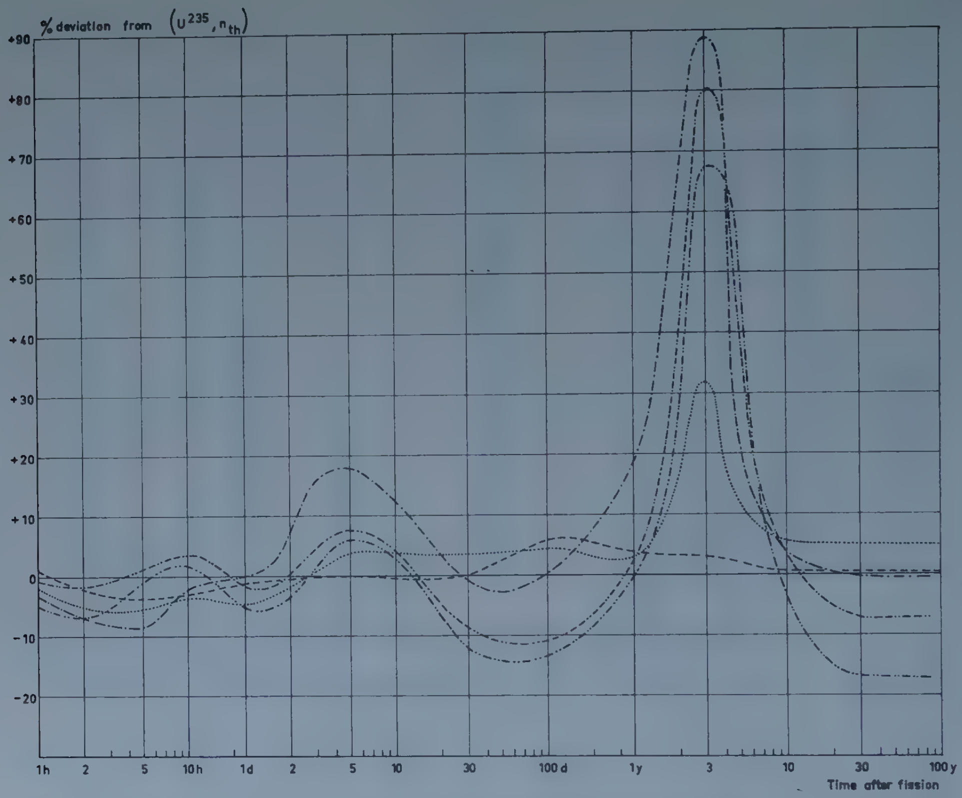

Fig. 5. Total number of γ:s per min and 10^4 fissions expressed as percentage deviation from (U^{235}, n_{th}) total γ. – – – – (U^{235}, n_f); – · – · – (Pu^{239}, n_f); · · · · · $(U^{238}, n\ )$; – – · · – – · · (U^{238}, n_{14}); – · · – · · – (U^{235}, n_{14}).

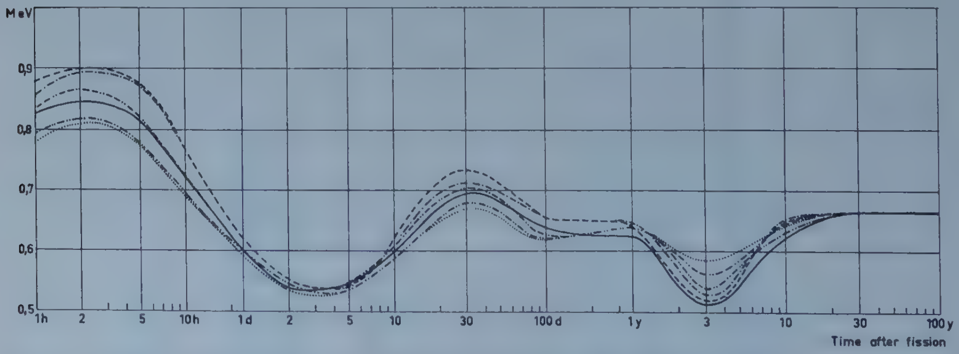

Fig. 6. Average γ-energy (MeV) for different times after instantaneous fission. – – – – (U^{235}, n_{th}); – · – · – (U^{235}, n_f); · · · · · · (Pu^{239}, n_f); – – · · – – · · (U^{238}, n_f); – – · · – · · – (U^{238}, n_{14}); ———— (U^{235}, n_{14}).

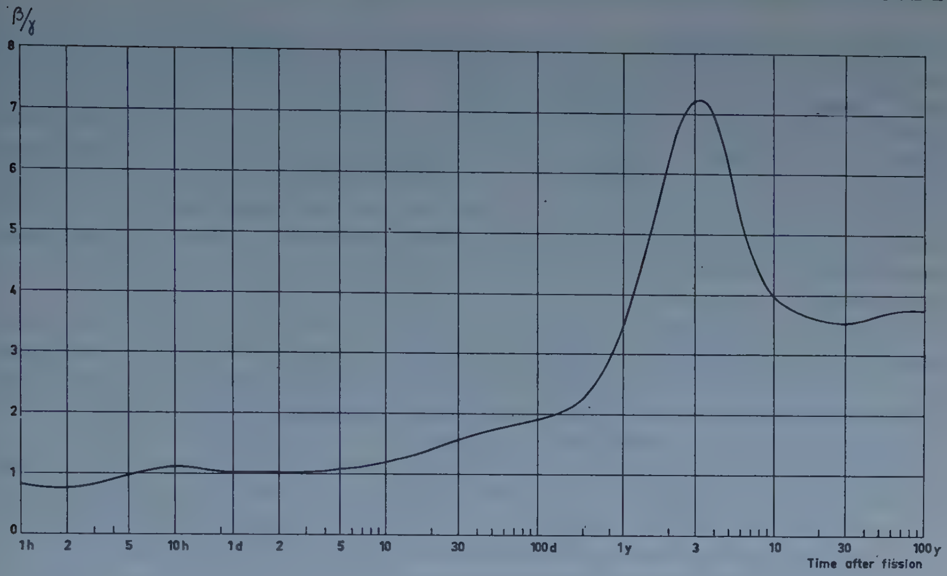

Fig. 7. β/γ for (U^{235}, n_{th}) as a function of time after instantaneous fission.

Discussion

Thermal neutron fission of U^{235}

As is evident from table 1, thermal neutron fission of U^{235} has been studied in a large number of papers. As a rule a fairly close match [51] is found between the calculated total gamma activity and experimental results as well as the values given e.g. by Way and Wigner [2], Borst [24], Day and Cannon [24], Hill and Lanzl [25], Brady and Turkevich [26]. This seems to be true for almost any choice of fission yields and decay data which of course depends upon the fact that the number of fission products is very large and thus errors in the individual isotope data tend to cancel. If one however examines the gamma energy distribution there appear differences which are larger the finer the energy group division.

The extensive work of Blomeke and Todd [16] is based on yield and decay data, current as of 1955. However, only four energy groups (0–0.25; 0.26–1.00; 1.01–1.70; and > 1.70 MeV) are used which should tend to reduce the influence of changes based on more recent data. Comparing e.g. the third energy group with the present calculation it is found that large differences exist. The reason for this is to be found in the decay data of Blomeke and Todd. Among the more important fission products the following changes could be pointed out as an example: 2.7 h Sr^{92} 1.38 MeV 90 % (B and T: 0 %), 3.6 h Y^{92} 0.94 MeV 21 % (B and T: 0 %); 5.3 d Xe^{133} 0.081 MeV 37 % (B and T: 100 %), 12.8 d Ba^{140} group II 22 % (B and T: 110 %); 290 d Ce^{144} group I 20 % (B and T: 50 %). In conclusion it might be said that the work of Blomeke and Todd has to be used with caution if reasonably accurate results are to be expected.

The work of Perkins and King [18] has been extended by Knabe and Putnam [21] to give the gamma distribution divided into 12 energy groups. Their input data are current as of 1957. For some fission products with unknown decay properties an attempt was made to derive such data theoretically. Perkins and King emphasize that this procedure is subject to large error but that it "represents a much better approximation to the truth than to neglect completely the probable presence of gamma radiation". On the other hand it might perhaps be argued that this procedure should not have been used when published data on the gamma decay properties existed, as was the case with Y^{93}, Zr^{97} and Te^{133m}. From additional data now available on Se^{83}, Y^{94}, Ru^{105} and Sn^{126} it appears that Perkins and King have accounted for about 75 % of the energy given off by these fission products. As was to be expected however, their theoretical method could not foretell the actual γ-energies with any great success.

Comparing the γ-spectra of Knabe and Putnam with those calculated here demonstrates deviations which sometimes are appreciable. From 30 days to 3 years there is a 30–50 per cent difference in group II which probably is explained by the fact that the γ-lines of Zr^{95} have been carried in group III instead of II (at least by Perkins and King). This would perhaps explain the difference that exists in group III which in the same time interval is up to 100 times comparing [21] with this work. A contribution to existing differences in groups I and II may as well arise as a result of the probable omission of Sb^{125} in the calculations of Perkins and King. Still other differences exist between this work and [18] and [21]. They are usually smaller than a factor of 2 and can probably be explained by the introduction here of more recent data.

Scoles' calculation [19] is rather extensive, dividing the gamma energies into 28 groups. It has however only been possible to compare the results of this paper with Scoles' earlier work as the more complete calculation has not been available. In the early paper Scoles uses only 6 energy groups and for operating and shutdown times which are not comparable to simultaneous fission conditions. The total gamma energy is however found to be almost identical in this and Scoles' work.

A comparison with the data of Nelms and Cooper [23] is complicated by the fact that their choice of energy group limits and decay times is rather unusual. As their decay data are current as of 1957 and the yield values not later than 1951, differences between their work and this are to be expected. This is also found to be the case, e.g. a factor of 3 at one hour for 1.5–1.9 MeV or a factor of 4 at 10 days for 0.0.–0.1 MeV. This last difference is large over the entire decay time studied and as the values of Nelms and Cooper consistently are higher than those calculated here, the probable reason is to be found in a difference of the conversion factors used. The γ-line around 3.5 MeV at 0.5 hours which had no satisfactory explanation at the time has now been identified as belonging to 74 min La^{142} [47].

It is difficult to estimate the errors inherent in a calculation of the present type. The yield values are usually given with a 3 % absolute error but the relative error, e.g. in relation to the Ba^{140} and Mo^{99} yield, is smaller, 1 % being about the lower limit. The accuracy of the decay data is varying, but the more important fission products have usually been thoroughly studied why for them a 5 % error seems a reasonable assumption. On the other extreme there are some nuclides with unknown γ-decay properties for which the assumed γ-energies may be completely wrong. As each energy group often contains contributions from several nuclides there should be a tendency for the errors to cancel partly, when considering the sum. It is probable that the calculated spectra have a relative error (comparing different energy groups) of around 10 % on the average although there are exceptions, e.g. the energy group 1.2–1.29 MeV which at 1 hour may have an error of 100 % due to the assumed

Table 4.

		1 h	2 h	5 h	10 h	1 d	2 d	5 d	10 d	30 d	100 d	1 y	3 y	10 y	30 y	100 y
Total γ-activity in number of γ:s per min after 10^4 fissions	U^{235}, n_{th}	79.2	36.5	9.93	4.22	1.71	7.28–1	2.38–1	1.067–1	2.57–2	5.35–3	3.92–4	3.92–5	1.96–5	1.161–5	1.86–6
	U^{235}, n_f	79.9	35.7	9.59	4.10	1.69	7.26–1	2.38–1	1.063–1	2.57–2	5.67–3	4.06–4	4.05–5	1.97–5	1.167–5	1.87–6
	Pu^{239}, n_f	76.6	33.8	9.08	4.12	1.71	7.85–1	2.81–1	1.199–1	2.54–2	5.37–3	4.66–4	7.41–5	2.03–5	1.159–5	1.86–6
	U^{238}, n_f	77.5	34.5	9.39	4.09	1.63	7.17–1	2.48–1	1.109–1	2.66–2	5.59–3	4.05–4	5.18–5	2.07–5	1.219–5	1.95–6
	U^{238}, n_{14}	78.5	35.7	10.06	4.37	1.68	7.30–1	2.56–1	1.111–1	2.35–2	4.76–3	4.02–4	7.06–5	2.02–5	1.077–5	1.73–6
	U^{235}, n_{14}	75.2	34.0	9.82	4.28	1.62	7.03–1	2.51–1	1.099–1	2.25–2	4.64–3	3.90–4	6.56–5	1.89–5	9.63–6	1.54–6
Total γ-activity in MeV per min after 10^4 fissions	U^{235}, n_{th}	69.6	32.9	8.73	3.25	1.061	4.01–1	1.30–1	6.63–2	1.88–2	3.50–3	2.53–4	2.04–5	1.27–5	7.54–6	1.209–6
	U^{235}, n_f	68.4	31.9	8.38	3.14	1.045	4.00–1	1.29–1	6.47–2	1.84–2	3.71–3	2.64–4	2.14–5	1.28–5	7.61–6	1.216–6
	Pu^{239}, n_f	59.6	27.4	7.04	2.85	1.010	4.22–1	1.51–1	7.02–2	1.71–2	3.33–3	2.99–4	4.33–5	1.30–5	7.54–6	1.209–6
	U^{238}, n_f	64.6	29.9	7.70	2.96	9.82–1	3.87–1	1.34–1	6.76–2	1.88–2	3.48–3	2.59–4	2.92–5	1.34–5	7.93–6	1.268–6
	U^{238}, n_{14}	62.4	29.2	7.82	3.05	1.010	3.98–1	1.37–1	6.52–2	1.59–2	2.95–3	2.58–4	3.81–5	1.27–5	7.02–6	1.125–6
	U^{235}, n_{14}	62.2	28.7	7.95	3.07	9.79–1	3.87–1	1.37–1	6.55–2	1.56–2	2.95–3	2.44–4	3.38–5	1.175–5	6.25–6	1.001–6
Mean γ-energy (total MeV divided by total number of γ:s)	U^{235}, n_{th}	0.878	0.901	0.879	0.769	0.620	0.551	0.546	0.621	0.733	0.654	0.644	0.520	0.649	0.663	0.663
	U^{235}, n_f	0.855	0.894	0.873	0.766	0.618	0.551	0.540	0.609	0.714	0.655	0.650	0.528	0.653	0.663	0.663
	Pu^{239}, n_f	0.778	0.811	0.775	0.691	0.591	0.537	0.537	0.586	0.672	0.621	0.642	0.585	0.643	0.663	0.663
	U^{238}, n_f	0.833	0.867	0.820	0.723	0.602	0.540	0.542	0.609	0.706	0.623	0.641	0.563	0.647	0.663	0.663
	U^{238}, n_{14}	0.794	0.818	0.777	0.697	0.601	0.545	0.534	0.587	0.679	0.619	0.642	0.539	0.630	0.663	0.663
	U^{235}, n_{14}	0.827	0.844	0.816	0.718	0.604	0.551	0.546	0.596	0.696	0.637	0.627	0.514	0.622	0.663	0.663
Total number of γ:s as percentage deviation from (U^{235}, n_{th})	U^{235}, n_f	+0.9	−2.2	−3.4	−2.9	−1.2	−0.3	+0.3	−0.4	+0.3	+5.9	+3.6	+3.1	+0.5	+0.5	+0.5
	Pu^{239}, n_f	−3.3	−7.4	−8.6	−2.4	0.0	+7.8	+18.0	+12.4	−1.1	+0.3	+18.7	+89	+3.6	−0.2	−0.2
	U^{238}, n_f	−2.1	−5.5	−5.4	−3.2	−4.7	−1.5	+4.2	+3.9	+3.8	+4.5	+3.1	+32	+5.7	+5.0	+4.9
	U^{238}, n_{14}	−0.9	−2.2	+1.3	+3.5	−1.8	+0.3	+7.7	+4.1	−8.6	−11.1	+2.3	+80	+3.4	−7.2	−7.2
	U^{235}, n_{14}	−5.1	−6.9	−1.1	+1.5	−5.3	−3.5	+5.8	+3.0	−12.4	−13.4	−0.6	+67	−3.5	−17.1	−17.1
Total number of β:s	U^{235}, n_{th}	65.1	27.5	9.59	4.73	1.79	7.50–1	2.56–1	1.297–1	4.05–2	1.022–2	1.37–3	2.83–4	7.76–5	4.08–5	6.98–6
β/γ	U^{235}, n_{th}	0.821	0.755	0.966	1.121	1.044	1.030	1.077	1.22	1.58	1.91	3.48	7.21	3.97	3.52	3.75

γ-line of Rb^{91m}. The absolute errors of each energy group may be of the order of 15 % at 1 hour but should decrease with encreasing decay time.

It could finally be pointed out that a calculation of this kind, dealing with instantaneous fission, may be utilized in the calculation of continuous fission γ-spectra if each decay time is taken as representative of a time interval, e.g. the 1 hour spectrum may be used for the period 0.7–1.5 hours, the 2 hour spectrum for 1.5–3 hours etc. In this way even a case with time variation of the neutron flux may be treated.

Fission with 14 MeV neutrons and fission neutrons

The only other calculation available for a comparison with this work is that of Dillon and Burris. Such a comparison is however pointless as these authors present only the total γ-decay and use data which (like those of Blomeke and Todd) are current as of 1955. The origin of their yield values is furthermore still uncertain.

It is apparent from Fig. 5 that the fission modes considered here differ little from thermal neutron fission of U^{235}. The exceptions are (Pu^{239}, n_f), (U^{238}, n_{14}) and (U^{235}, n_{14}) in the time interval 1.2–6 years where deviations greater than 30 % occur. This depends largely upon the yield of Rh^{106} and Sb^{125} being much larger for 14 MeV and fission neutrons.

The average γ-energy (Fig. 6) does not change much from one fission mode to another. As a result thereof and because for Rh^{106} $\bar{\gamma} = 0.63$ MeV; $\beta/\gamma = 2.9$; it is to be expected that the peak in β/γ (Fig. 7) for (U^{235}, n_{th}) will not be equally pronounced for (Pu^{239}, n_f), (U^{238}, n_{14}) and (U^{235}, n_{14}). The calculations do however not give the possibility of a direct check of this.

The yield values used in this part of the calculation are more uncertain than those of (U^{235}, n_{th}). This is e.g. evident from a comparison with some results (52) that were published after the conclusion of these calculations. For (U^{238}, n_{14}) some yield values are higher than those assumed in table 2 with up to 40 %. The error per energy group is thus in some cases probably larger than the 10 % and 15 % suggested for (U^{235}; n_{th}).

Nuclear weapons fallout

There are a number of circumstances which make the fallout appraisal tricky. One of them is the occurrence of neutron induced acitivity either in the weapon itself as e.g. Np^{239} from the uranium tamper of tactical weapons, U^{237} from the tamper of "dirty" weapons, etc. or in the environment of an explosion, e.g. neutron capture in the soil that is carried aloft in a ground surface explosion. These activity contributions are not to be discussed here. It should just be noted that for certain time intervals after a nuclear explosion such induced activities may dominate the fallout activity [12, 53–55].

Another complication is often termed fission product fractionation. During the formation of the atomic cloud there are condensation and occlusion phenomena taking place which may affect the radioactive composition of the fallout particles. As a result these particles may contain fission product mixtures which differ from the transient equilibrium values [56–58].

A third factor to be kept in mind is the neutron flux dependence of fission product formation. This effect is quite marked in connection with thermal neutron fission [16], (III) and a similar phenomenon has been noted for nuclear weapons in that transuranium elements are formed [59, 60]. It is however not to be expected [61] that large changes will be produced in a nuclear weapon fission product mixture as the fast neutron capture cross sections of the newly formed fission products are small.

Conclusions.—In the evaluation of the health hazards from nuclear weapons fallout γ-radiation it is in general sufficient to consider fallout as equivalent to fission products formed in thermal neutron fission of U^{235} as the total γ-decay and the average γ-energy are closely comparable most of the time. In the time interval 1.2–6 years an exception to this rule should be made if the fission modes (Pu^{239}, n_f), (U^{238}, n_{14}) and (U^{235}, n_{14}) are considered and an accuracy of better than 30 % is desired.

Work is needed on the influence of neutron induced activity and fractionation phenomena on the γ-decay of fallout. The influence of the neutron flux on the fission product formation is probably not too important but a study of this effect would clarify the fallout problem.

The results presented may alternatively be used in a computation of fallout characteristics from different kinds of nuclear weapons (if the essential design features are known) or as a means of analyzing fallout to get some information on actual weapons designs. The latter possibility may be important e.g. in connection with an estimate of the stratospheric fallout content.

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